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"ANNULO CINGITUR": THE SOLUTION OF THE PROBLEM OF SATURN

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When Pierre Gassendi died, in October 1655, he had been anxiously awaiting the expected 'solitary' appearance of the planet Saturn.[1] Although he had made numerous observations of this "celestial Proteus" over the preceding two decades, he had not been able to formulate an hypothesis which could account for the various appearances of Saturn. Death not only robbed him of the opportunity to witness the disappearance of the mysterious "anses", but also of participating in the lively discussions about the conjectures and hypotheses concerning Saturn's appearances which were formulated shortly after this 'solitary' appearance. In the paper "Saturn and his Anses", in the previous issue of this journal, the problem of Saturn was traced from its beginning in 1610 to the 'solitary' appearance of 1655/56.[2] It is the purpose of this paper to discuss the different hypotheses put forward between 1656 and 1665, and to trace the events which led to the eventual acceptance of one of these, the ring-hypothesis of Christiaan Huygens.

Although the improvement of the telescope was certainly one factor contributing to the solution of the problem, it is simply wrong to speak of "the resolution of the so-called *ansae* or 'handles' into one encircling ring by Huygens".[3] The figures drawn, for example, by Galileo in 1616 and Divini in 1649,[4] show that when the ring[5] was in its most open aspect with respect to the Earth telescopes were good enough, at a very early stage, to show something which a modern observer could easily interpret as a ring. But neither Galileo nor Divini (nor anyone else) made the "gestalt switch" from "seeing" a globe with two attached "handles" to "seeing" a globe surrounded by a ring.[6] Nor can we speak of such a sudden change in perception in the case of Huygens: when he formulated his ring-hypothesis the anses were invisible. The manner in which Huygens arrived at his hypothesis depended as much on his Cartesian convictions as it did on the excellence of his telescope, as will be shown below.

The ring-hypothesis was by no means the only proposed solution, and for a time, therefore, there was a competition between hypotheses—a competition which sheds an interesting light on the workings of the scientific community. Needless to say, personal factors entered the professional conflicts. Furthermore, Huygens's hypothesis was not perfect: there were quantitative problems which took almost a decade to be resolved, while Huygens's stubborn insistence on thick, solid ring also helped delay the acceptance of his hypothesis. Thus, only after suitable adjustments had been made to the original hypothesis could one say, as did Robert Grant two centuries later: "Nothing can be more convincing or beautiful than the explanation which this theory affords of the various phenomena presented by this planet."[7]

Between 1656 and 1665, then, a number of models to explain Saturn's appearances were put forward. Some of these were mere suggestions, but others were presented as fully articulated theories. The chain of events starts with Huygens, who took up the grinding of lenses for telescopes and microscopes

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early in 1655.[8] By March of that year, he and his older brother Constantijn had constructed a 12ft telescope which was good enough to enable him to make an astronomical discovery. On the 25th of that month, Huygens noticed a small star, roughly on the extension of Saturn's anses, and his suspicion that it might be a satellite of Saturn was confirmed over the next few nights of observation.[9] But Huygens did not announce his discovery immediately. First he determined the satellite's period, and then, in June 1655, he sent out an anagram in which the discovery was hidden.[10] The solution of this anagram was not circulated until the autumn of that year.[11]

During the winter 1655/56, the two brothers devoted their efforts to making a longer, more powerful telescope; the new, 23ft instrument was first used on 19 February.[12] But eleven days earlier Huygens had already written to one of his correspondents about his "System of Saturn".[13] Therefore, any clue he got from a telescope must have been obtained with the help of his 12ft effort, which was not greatly superior to those of other good telescope makers: both Hevelius and Wren had seen the little star near Saturn, but had taken it to be a fixed star.[14] This time Huygens did not delay. By the middle of March 1656 he was circulating a printed sheet entitled *De Saturni luna observatio nova*, which contained a full account of the new satellite, a prediction that Saturn would recover its anses in April 1656, and a new anagram—this one about Saturn's appearances: *aaaaaaaccccccdeeeeeghiiiiiiiiillllmmnnnnnnnnn nnooooppqrrsttttttuuuuu.* The anagram was registered ". . . so that, if someone perhaps thinks that he has found the same thing, he will have time to make it known. . .".[15] This challenge did not remain unanswered.

Huygens did not publish his "System of Saturn" for more than three years, for several reasons, not the least of which was his work on the pendulum clock.[1] In the meantime several hypotheses about Saturn's appearances were published and several more were circulated in manuscript form. The first to see the light of day was the hypothesis of Hevelius, who had been interested in the problem of Saturn since the 'solitary' appearance of 1642. For some time he had had it in mind to publish something on this planet, but he had waited until he had observed the 'solitary' appearance again.[17] This had occurred in the winter of 1655/56, and Hevelius, who unlike so many of his contemporaries never suffered from a reluctance to publish his work, quickly finished a tract on the subject. *Dissertatio de nativa Saturni facie* was published in June 1656.[18]

In 1642, when the planet was 'solitary', Hevelius had seen Saturn's central body perfectly round. But in the middle 'forties, when the central body was flanked by two handles, he had seen it egg-shaped. These observations were published in his *Selenographia* of 1647,[19] and on the basis of them Johannes Phocylides Holwarda, the Frisian astronomer, had suggested in his *Philosophia naturalis* of 1651 that perhaps Saturn had an egg-shaped central body to which two crescent-shaped arms were attached.[20] Hevelius made this suggestion the basis of his hypothesis. He proposed that Saturn's shape was indeed that of an egg, with two attached arms, as shown in Figure 1. The whole formation rotated about the axis indicted, and seen from the side, Saturn would appear round and 'solitary' as it did in 1642 and 1656.[21]

The rotation of Saturn with respect to the Earth could be explained by supposing that the planet moved on an epicycle which rotates on Saturn's

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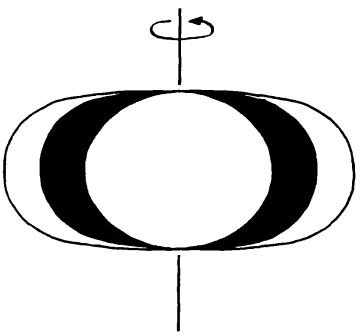

FIG. 1. Hevelius's hypothesis of Saturn. The entire formation rotated about the axis.

orbis magnus eccentricus (*i.e.*, the deferent), or by supposing that it moved in an elliptical orbit without rotating with respect to the fixed stars.[22] The most open phase, called *elliptico-ansatus* by Hevelius, always occurred, according to him, at Saturn's aphelion and perihelion, which he located at 27° Sagittarius and Gemini, respectively; the appearance called *monosphaericus* occurred at mean longitudes, in Pisces and Virgo.[23] Hevelius summarized the phases and their places in the zodiac in one convenient table of actual observations made between 1610 and 1656, and also gave the reader ephemerides for the next fifty years. The next 'solitary' appearance was predicted to last from March 1672 to April 1673.[24]

The obvious problem with Hevelius's hypothesis was the incompatibility of his *elliptico-ansatus* and *trisphaericus* appearances. He made an attempt to explain this problem away:

> . . . that [*trisphaericus*] appearance arises only from hallucinated vision, and . . . because of the immenseness of the distance and the weakness of the emanation, or because of distortion of the sense [of vision], the said bodies may be perceived by us less well articulated and those interior parts cannot be seen distinctly concave. We have, in fact, also learned from opticians that irregular bodies, seen from a distance in a certain way, appear spherical, especially when positioned obliquely, when the natural body always appears deformed. Because the more remote and smaller the objects are, the less perfectly they are perceived. We grant therefore that Saturn's adhering globes appear in fact entirely round to us, but that, all the same, they are not at all exactly round.[25]

Hevelius's readers duly pointed out that it was still not obvious how those wide, crescent-shaped arms could contract into small, detached, round globes,[26] but Hevelius did not think this shortcoming important. As time went on, improvements could be made in his hypothesis, but at least he had fixed the period and the progression of the phases.[27] Although others may have thought that this progression was now obvious, Hevelius was right in arguing that he had been the first to publish this important information.[28]

A theory of a different nature was put forward by the French mathematician Gilles Personne de Roberval, as a response to Huygens's challenge. Roberval supposed that Saturn had an equatorial zone from which vapours rise at certain times to collect above the planet, forming a band about the planet. These

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vapours are much less dense than terrestrial vapours, and can rise to great heights. Sometimes they fill the space above the torrid zone completely, while at other times a transparent space of air is left between the planet's surface and the collected vapours.[29]

According to Roberval, then, Saturn would appear solidly oval when all the space above the torrid zone is filled with the emanation, and the elongation would, of course, be east-west, because the torrid zone is an equatorial zone. When there was some space left between the vapours and the surface of the planet, Saturn would appear flanked by two stars, since the vapours would appear opaque to us only where a double thickness of them is presented to our vision; at all other places the emanations would be thin enough to be transparent. When there was a great distance between the surface and the vapours, and the band of vapours was narrow, the planet would appear handled. When there were no emanations, the planet would, of course, appear single and round.[30]

The major objection to this hypothesis was that it was purely qualitative. Roberval should have paid more attention to the quantitative aspects: the period and progression of the phases. As Huygens pointed out, there is nothing haphazard about this progression, and if the appearances were caused by emanations how could Roberval explain the fact that the various phases appear so promptly on schedule?[31] The strength of the hypothesis lay not so much in its explanation of the appearances (after all, one can explain any shape by postulating an appropriate emanation) as in the structural approach to the problem. Roberval's objection to Huygens's ring-hypothesis, that it was ". . . une machine toute d'art et dont il n'y avoit aucune image dans la Constitution du monde . . .",[32] expressed the feelings of many men.

Another response to Huygens's challenge came all the way from Sicily. When Giovanni Battista Odierna, the mathematician of the Duke of Palma, read Huygens's sheet, *De Saturni luna*, he was so aroused that he rushed into print, so as not to be "defrauded of his priority".[33] His little tract, *Protei caelestis vertigines*, came off the press early in 1657.[34] Odierna's hypothesis was that Saturn is an elliptical body with two black spots:

> Although Saturn appears triple like a great celestial Proteus, or like the Cerberus of the heavens, and fashions himself into different shapes, he is nevertheless simple, and his great single mass persists constantly in its entirety, but does not, like the rest of the heavenly bodies, rejoice in a roundness of body, but rather presents an elliptical or oviform figure, by virtue of which he represents a chicken's egg, or portrays the likeness of the fruit of an olive-, plum-, or palmtree. The surface is spotted like the Moon, where it shows raging oceans enclosed by land.[35]

Saturn's ovoid body makes one complete revolution about its minor axis during every period of Saturn. Thus, twice during Saturn's journey around the Earth the planet appears round without handles, and twice it appears in its most open position. The full-faced figure of Saturn shown by Odierna (see Figure 2) is as good a representation of what could be interpreted as a ring as was drawn before Huygens actually set out to draw a ring; it was based on observations

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FIG. 2. Saturn as seen by Odierna; from *Protei caelestis vertigines.*

made with a telescope which, as Odierna lamented, only magnified twenty times.[36]

Obviously, Odierna was in the same dilemma as Hevelius was when it came to reconciling the 'handled' with the triple-bodied appearance, but he made no attempt to deal with this problem. In his *Systema Saturnium* Huygens invited Odierna to paint black spots on an egg and discover for himself why his hypothesis could not save the phenomena. But by the time Huygens's book reached Sicily, Odierna had already died.[37]

One theory which was formulated during this period but did not become widely known until several years later was that of Christopher Wren. Although regular observations of Saturn had been made in Oxford since 1649 (the year in which Wren entered the university), his own interest in the problem of Saturn dated from 1654.[38] While he and Sir Paule Neile observed the planet through progressively better telescopes made by Neile, they were also kept informed by William Balle, who was making observations with a 12ft Italian telescope (probably made by Eustachio Divini).[39] In 1655 Balle notified Wren that he had seen a dark line across the face of Saturn—undoubtedly the shadow of the ring on the body.[40]

In 1656 John Wallis, who was in close touch with Wren, related Wren's thoughts on this problem to Huygens. His letter shows that the men in Oxford realised that many of the observations reported in literature had to be discarded. They were thinking in terms of a rotating motion about the major axis of the anses, and realised that the anses could be so thin that ". . . with only the edge turned towards our eyes, . . . it disappears and only the spherical body of Saturn appears".[41] But in order to be sure that they were on the right track, they needed to know whether the anses became thinner and finally disappeared, or whether they became shorter. If the latter were the case, their ideas were obviously wrong. Wallis asked Huygens if he could supply the crucial observation.[42]

Huygens could easily have obliged his English colleagues, but he chose not to do so. It was therefore not until December 1657 that Wren and Neile were able to confirm their suspicion that ". . . the Armes of [Saturn] kept their length. . .".[43] Wren now quickly wrote a tract entitled *De corpore Saturni*, in which he put forward his hypothesis. According to him, Saturn's central globe was surrounded by an elliptical "Corona", which touched it at two opposite points on Saturn's

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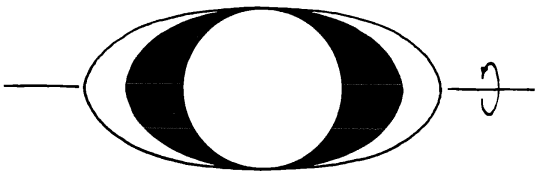

FIG. 3. Wren's hypothesis of Saturn. The corona rotated or librated about axis shown.

equator, as shown in Figure 3. Body and corona rotated about the major axis of the corona once during every period of Saturn, while this axis always remained perpendicular to the line joining Saturn and the Sun. At aphelion and perihelion the corona would be at right angles to Saturn's orbital plane, while at mean longitudes it would lie in that plane, presenting its edge to the Earth and the Sun.[44] The thickness of the corona ". . . is not sufficient to be seen in any way by the inhabitants of the Earth, and for this reason the corona may be taken as a mere surface".[45] There were other possibilities: perhaps the corona rotated independently of the central globe, or perhaps the planet and globe had a rocking motion, not a rotating one.[46]

With the exception of the varying width between the inside and outside edges of the corona—a relatively minor problem—Wren's model saved the phenomena effectively. How the triple-bodied appearance, now deemed an illusion, arose from an elliptical corona, was explained by means of optics and common sense.[47] But Wren's hypothesis was the final product of careful model building—both mental and physical—and it lacked that last conceptual leap, the realisation that the apparent ellipse could be an oblique projection of a circle. The hypothesis was thus literally lacking a dimension. When the ring-hypothesis was made known to Wren, he immediately saw the light:

> But when in a short while after, the Hypothesis of Hugenius was sent over in writing, I confesse I was so fond of the neatnesse of it & the naturall simplicity of the contrivance, agreing so well with the Physicall causes of the heavenly bodies, that I loved the invention beyond my owne. . . .[48]

As we shall see below, it was only through a coincidence that Wren's tract became more widely known, a few years later.

Huygens fortunately gave an account of the mental process by which he arrived at the realisation that a ring could explain all Saturn's appearances. As we have seen, his first good telescope, the 12ft effort finished in March 1655, furnished him with all the clues he needed. This instrument magnified about fifty times.[49] His first recorded observation of Saturn dates from March 1655, shortly after he had finished this telescope (see Figure 4).[50] The anses were then already very narrow, and they disappeared entirely later that year, not returning until after Huygens had formulated his hypothesis.[51] That is, before he arrived at his hypothesis Huygens never observed the planet when it was showing anything that could actually be "seen" as a ring.

In his *Systema Saturnium*, however, Huygens tells the reader that his first observation (see Figure 4) gave him an important clue: even when the anses are very narrow they have the same length as when at their widest.[52] This was

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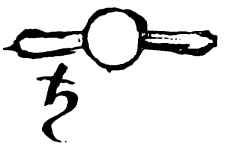

FIG. 4. Saturn as seen by Huygens in March 1655; from *Oeuvres complètes*, i, 322.

an indication that the triple-bodied appearance was an illusion caused by inferior telescopes, a conclusion which was, of course, easily verified. The anses, then, become progressively narrower until they disappear. But Wren had guessed as much, and had been able to verify it in 1657. Moreover, the dark band which Huygens saw across the face of the planet[53] was being observed in England as well. There had to be another factor.

Huygen tells us that he began considering the system of Saturn and its moon analogously to the Earth-Moon system. If our Moon goes around the Earth in about 29 days, while the Earth turns on its axis once every 24 hours, then the 16-day period of Saturn's moon must mean that the planet itself turns on its axis in about half a day. Furthermore, as in the Earth–Moon system, Saturn's axis of rotation must be perpendicular to the orbital plane of its moon, and this is also the plane in which the anses lie. All the matter between Saturn and its moon probably rotates about the same axis, with periods intermediate between half-a-day and 16 days. (Although Huygens does not specifically mention vortices in this connection, the Cartesian vortex conception obviously played a great rôle in this chain of reasoning.) If the anses turn about this axis in less than 16 days and yet show no short-term changes, then they must have rotational symmetry about Saturn's axis.[54] At this point, Huygens realised that a ring would satisfy this condition and would also explain Saturn's appearances. Whether this realisation came to him as a sudden insight or as the fruit of arduous trial-and-error considerations is not revealed by the author.

Although *Systema Saturnium* was not published until July 1659, Huygens did not keep the ring-hypothesis entirely secret. He confided in Boulliau in 1657, and allowed Chapelain to reveal it at a meeting of the "Montmor Academy" in the spring of 1658.[55] Wallis was told by letter early in 1659.[56] This knowledge served to heighten anticipation, and when the tract finally saw the light of day, readers were not disappointed. It lived up to its title, being a complete treatise on the system of Saturn.

Huygens carefully describes his telescopes and discusses his observations of other celestial phenomena.[57] He relates the whole history of his observations of Saturn's moon, and gives the elements of its orbit fairly accurately.[58] Since it was he who discovered Saturn's satellite, Huygens argues that his telescopes are better than those of anyone else, and therefore he is justified in sitting in judgment on the observations of others.[59] After criticising the theories of Hevelius, Roberval and Odierna, and ascribing the failure of these men to arrive at the correct solution to the puzzle to the inferiority of their telescopes, Huygens presents the solution of the anagram which he had published in *De Saturni luna*, three years earlier: *Annulo cingitur, tenui, plano, nusquam cohaerente, ad eclipticam inclinato*, or, "He is surrounded by a thin flat ring which does not touch him

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anywhere and is inclined to the ecliptic".[60] The rest of *Systema Saturnium* is an exhaustive exposition of how this ring, which stays parallel to itself, can account for all Saturn's appearances, fixing its inclination to the ecliptic and its points of intersection with the ecliptic, and making predictions as to when future appearances will be seen. The lucidity of the tract is well-illustrated by the explanatory figure used by Huygens (see Figure 5), which is still used today to explain the appearances.[61]

Although the solution of the anagram indicated that the ring was thin, its thickness was not negligible according to Huygens: his proposed ring was a solid structure.[62] This made it difficult to explain its periodic invisibility. Huygens postulated that the edge of the ring was covered with a material which does not reflect light at all, or is so smooth that reflected sunlight reaches the Earth from only one point on its surface. He was aware of Wren's thought on this subject, but he specifically rejected the more elegant construction of a thin ring.[63] For various reasons, the dark band which he had seen across the disk of Saturn could not be the shadow of the ring on the body, according to him, and he stubbornly insisted that it was the dark outside edge of a thick ring.[64]

It would be a mistake to suppose that Huygens's hypothesis met with immediate and universal approbation. It ran into serious opposition on several fronts. The major stumbling block was the unprecedented nature of a solid ring in the heavens, encircling a planet but not touching it, and the *ad hoc* device to explain the periodic invisibility of the ring. Claude Mylon wrote to Huygens:

> . . . J'ay pensé que l'umbre de l'Anneau pouvoit contribuer quelque chose a fair paroistre la petite bande noire sur le Corps de Saturne, pour respondre a ceux qui ont difficulté d'admettre que la superficie convexe de l'Anneau soit polie et d'une maniere a ne point reflechir de Lumiere que ses bras ne seroient pas visibles hors la planette quand nostre oeil est dans le plan de l'Anneau a cause de son peu d'espaisseur. . . .[65]

Huygens had great respect for the opinions of Boulliau, who had been the first scientist to be informed of the ring-hypothesis. When *Systema Saturnium*

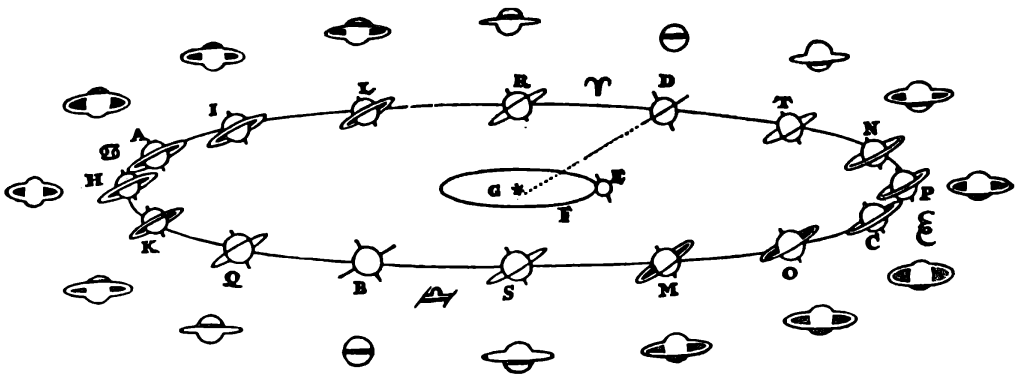

FIG. 5. Figure used by Huygens to show how a ring can generate the various appearances of Saturn; from *Oeuvres complètes*, XV, 309.

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came out, Boulliau took considerable time to ponder the matter, and then expressed severe doubt:

> Vous establissez fort bien vostre hypothese, & elle procede regulierement, pourveu que vous puissiez persuader que ce cercle puisse devenire invisible a cause du peu de consistance en espesseur qu'il a en soymesme. Je scay que la nature a pu faire un cercle autour de ce corps la, & que par la raison qui fait que la terre est suspendu; en aëre libero, un anneau peut aussi y estre suspendu; neantmoins il vous faut encore quelques experiences pour demonstrer absolument ce que vous posez.[66]

The theory would be better, according to Boulliau, if the ring were supposed to be very thin. These comments of Mylon and Boulliau are typical of the reception of the ring-hypothesis.

Huygens had determined the inclination of the ring-plane (Saturn's equatorial plane) to the ecliptic to be $23\frac{1}{2}°$, and he considered this a strong argument for the Copernican theory.[67] He had also measured the ratio of the diameters of the ring and the central globe to be 9:4. These two figures meant that at its maximum inclination with respect to the Earth the ring should form an apparent ellipse not quite wide enough to hide the planet's poles. Boulliau and others knew this to be an erroneous prediction, for they had seen the apparent ellipse of the ring enclose the body of the planet completely in the late 1640s. Boulliau pointed this out to Huygens, and used it as the reason why he preferred another hypothesis: perhaps the ring was very thin and elliptical, and was attached to the planet in two places.[68] This was substantially the same as Wren's hypothesis, although there is no evidence to suggest that Boulliau was at this time aware of the existence of Wren's hypothesis.

Hevelius's comments on *Systema Saturnium* are preserved in a long and frank letter to his good friend Boulliau. He was rather upset at Huygens's claims as to the superiority of his own telescopes. Hevelius argued that his telescopes were just as good as those of Huygens, and that he had seen the satellite many years before Huygens had discovered it, but had thought it to be a fixed star.[69] He did not think that a thick ring was a very plausible device: "If, in fact, it is such a huge structure, it ought to have a very noticeable thickness or depth, in order that during the very rapid motion it does not completely collapse, which otherwise would happen, not without great detriment and confusion to the celestial bodies!"[70] And as to the non-reflecting edge of the ring, ". . . who does not see that these reasons are dull and that they cause the very contrary of the matter?"[71] Since Hevelius had already published all the important information about the progression and period of the phases (for which Huygens had given him no credit whatsoever), Huygens had added nothing new to this aspect of the problem.[72]

With regard to the shape of the central body, Hevelius took great exception to Huygens's criticism: ". . . does Huygens perhaps suppose that I and others are not able to discern what is elliptical or spherical, or that it was invented by my mind . . . or rather that I dreamt it? No, by Hercules!"[73] In a more restrained letter to Huygens himself, he wrote that in 1663 or 1664 Huygens would see that the central body is not spherical, but elliptical, and that would end their

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disagreement.[74] Huygens replied that by 1663 the central body would be partially hidden by the ring, so that one would not be able to tell whether it was spherical or elliptical.[75] Obviously these different criteria for verification were reflections of the two different hypotheses. Huygens pointed out that near the next edgewise appearance the shape of the anses would settle their argument, for then Hevelius would be able to see for himself that they did not decrease in length.[76]

Although many of his younger colleagues praised the ring-hypothesis (except for the ring's supposed thickness), the reactions of many older men were, as shown by the comments of Boulliau and Hevelius, not very encouraging. From Italy the reaction was initially even more disappointing. *Systema Saturnium* was dedicated to Prince Leopold de' Medici, the patron of the recently founded Accademia del Cimento.[77] For various reasons the Prince did not reply to Huygens personally, and the approbation which the latter had sought was some time in coming. Prince Leopold was aware of certain obvious shortcomings of Huygens's hypothesis, and he was uncertain as to the quality of Huygens's telescopes. He therefore turned to his academy for advice.[78] But in Rome Huygens's tract had aroused the ire of Honoré Fabri, a powerful French jesuit, who took exception to Huygens's frank Copernicanism. Fabri teamed up with the telescope maker Eustachio Divini, whose telescopes had, supposedly, been slighted by Huygens, and in the summer of 1660 a polemic tract entitled *Brevis annotatio in systema Saturnium* appeared in Rome. It was written by Fabri, although Divini's name appeared on the title page, and it was dedicated to Prince Leopold.[79] The Prince was thus cast in the position of referee in this controversy.

Fabri rejected the ring-hypothesis and put forward his own hypothesis. All Saturn's appearances can be saved by supposing that the planet has four satellites, besides the one recently discovered by Huygens. These four satellites revolve about points *behind* Saturn with respect to the central Earth. Two smaller ones, which do not reflect light at all, revolve in one orbit, and two large ones, which do reflect light, revolve in a somewhat larger orbit. The

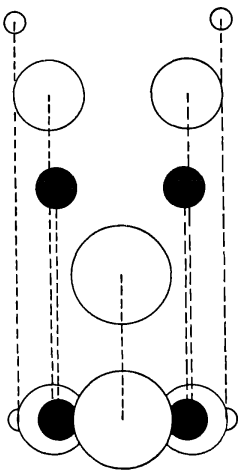

FIG. 6. Fabri's hypothesis, showing how six satellites can generate the 'handled' appearance.

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various formations of these four satellites with respect to the central body would explain all the observed appearances of Saturn.[80] It was not difficult for Huygens to find fault with this hypothesis, and he quickly issued a reply, entitled *Brevis assertio systematis Saturni*, in which he pointed out that the outline of the anses is elliptical, not circular, and also challenged Fabri to find the appropriate periods of these supposed satellites.[81]

Fabri's rejoinder, *Pro sua annotatione in systema Saturni*, published in 1661, brought the satellite hypothesis to absurd extremes. In order to explain the elliptical outlines of the anses he postulated two more light-reflecting satellites, which would appear partially at the sides of the other (larger) light-reflecting satellites. Figure 6 shows how Fabri now proposed to generate the 'handled' appearance. The imperfections of the telescope would cause the tips of the handles to appear elliptical.[82] But the problem of the periods of the satellites was completely ignored. It was obvious that Huygens was winning the battle, and Fabri practically admitted in *Pro sua annotatione* that the ring-hypothesis was superior to his own hypothesis. In fact, he admitted that he had trouble *not* seeing a ring when he observed Saturn through a telescope![83] Four years later he gave his approval to the ring-hypothesis in print.[84]

In the meantime, the Accademia del Cimento had undertaken a comparison of the two hypotheses. During the summer of 1660 the academicians made a number of observations of the planet, and detected for the first time the shadow of the body on the ring.[85] They also made models of both hypotheses, finding that Fabri's hypothesis was unable to account for any appearances other than the 'solitary' and the tri-spherical. Although the tests amounted to an endorsement of the ring-hypothesis, the members of the Accademia del Cimento had several reservations. They had not been able to reproduce the 'solitary' appearance of Saturn with a thick ring viewed edgewise, no matter what substance they used to cover the outside edge. Only when they had used a very thin ring and had taken great care to eliminate all roughnesses from its flat surfaces had they been successful in making it invisible when viewed edgewise.[86] This experimental proof that a (thin) ring could in fact account for all Saturn's appearances, including the triple-bodied appearance, was an important contribution to the solution of the problem. Although Huygens was perfectly correct in ascribing some of the appearances to inferior telescopes, many of his older contemporaries had found his way of dispensing with observations which did not fit his hypothesis arbitrary. Unfortunately, the reports of this very sophisticated experimental work were not published, probably because the results were so unfavourable to Father Fabri.[87]

In general, those (other than Huygens) who accepted the ring-hypothesis thought that Saturn was surrounded by a very thin ring. Huygens argued time and again that such a thin ring could not throw such a wide shadow on the central globe, and also claimed that he had seen the dark band where no shadow was predicted; the dark band had to be the dark outside edge of a thick ring.[88] He clung to this opinion for the rest of his life,[89] and in his posthumous *Cosmotheoros* he still argued that the ring was *at least* 600 German miles (about 2400 miles) thick.[90] He very quickly became isolated on this issue. His fellow scientists simply shrugged their shoulders and ignored Huygens's protests. During the decade of the 1660s, however, a different problem had to be settled.

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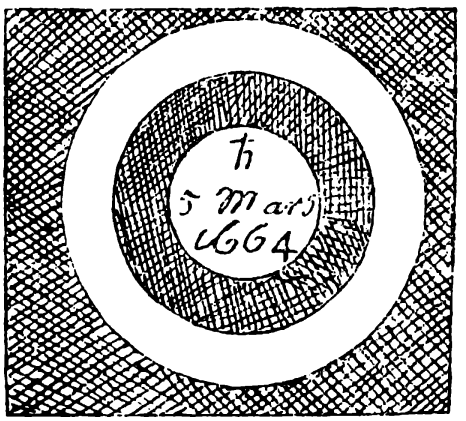

FIG. 7. According to Frenicle's suggestion, Saturn should appear in this shape twice during each period; from *Oeuvres complètes*, iii, 338.

By 1661, the inclination of the ring with respect to the Earth was by no means at a maximum yet, but already the apparent ellipse of the ring almost completely enclosed the planet. It was becoming obvious that Huygens's numerical values were in error.[91] Huygens wished to retain the $23\frac{1}{2}°$ inclination of the ring-plane to the ecliptic, and therefore he had to adjust the ratio of the diameters of the ring and body. In order to save the phenomena, he changed this ratio from 9:4 to 17:6, but without making any new measurements.[92] Bernard Frenicle de Bessy, a French mathematician, did not agree with this adjustment, and instead argued that the inclination of the ring was not constant. According to him the ring revolved about the major axis of its apparent ellipse once during Saturn's circuit about the Sun.[93] But surely, all those who had been making observations in the 1640s could testify that Saturn had never been seen surrounded by a circular ring, such as shown in Figure 7? In that case, Frenicle suggested, the ring was not circular but elliptical, but still had a rotating or rocking motion about its major axis.[94] This is the third time that we have encountered this hypothesis!

Frenicle's thoughts were brought to the attention of the Royal Society by Sir Kenelm Digby, and it was on this occasion that, on the insistence of other Fellows, Wren's hypothesis was exhumed and sent to Huygens and Frenicle.[95] Although both were informed that Wren had abandoned this hypothesis in 1659, neither could restrain himself from offering criticisms, and another controversy was avoided only because Wren refused to rise to the bait.[96]

But the problem of the ring's inclination would not go away. The ratio between diameters was much too large at 17:6, and other astronomers pointed out the discrepancy to Huygens. In 1665 Adrien Auzout asked Huygens to measure the ratio again, for he did not agree that it could be as large as 17:6. He also suggested that perhaps the inclination of the ring to the ecliptic was greater than $23\frac{1}{2}°$.[97] Finally, starting in 1667, Huygens (now settled in Paris) made new measurements of this inclination. The observation made with Picard ih August 1668, and published in the *Journal des sçavans*, led to a new value of "about 31°" for the inclination of the ring-plane to the ecliptic.[98] This figure, in fact, erred on the large side, but there would be no further problems in accommodating the disk of the planet in the apparent ellipse of the ring.

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Huygens now reverted to the 9:4 ratio of the diameters of ring and body, which is, of course, much more accurate than 17:6.[99]

Although Huygens made observations of heavenly bodies for the rest of his life, and continued making telescopes with his brother, he made no further celestial discoveries. In the 1660s he fell behind the first rank of observers, some of whom worked with telescopes which were significantly better than his best efforts. It took Huygens several years to verify the observation of the shadow of Saturn's body on the ring, made in Florence in the summer of 1660, with a telescope made by Eustachio Divini.[100] And within a few years, Divini's telescopes were surpassed by those of his fellow Roman, Giuseppe Campani.

In 1663 Campani observed Saturn with telescopes of 13 and 18 feet, and saw a central globe actually surrounded by a ring, as shown in Figure 8.[101] The text accompanying the figure, published in Campani's *Ragguaglio di due nuove osservazioni* of 1664, describes what Campani saw:

> . . . Saturn is surrounded by a circle, in appearance in the shape of an ellipse, situated in such a manner about the globe that the superior part . . . hides a portion of the said globe, while, on the other hand, the inferior portion of the circle . . . is hidden and partly covered by the same globe, so that the inferior part remains behind, and the superior part in front of the star, as is sensibly understood from the apparent place and position of the circle and from those lightly shadowed outlines of the same circle, as well as of the globe or disk of Saturn. . . .[102]

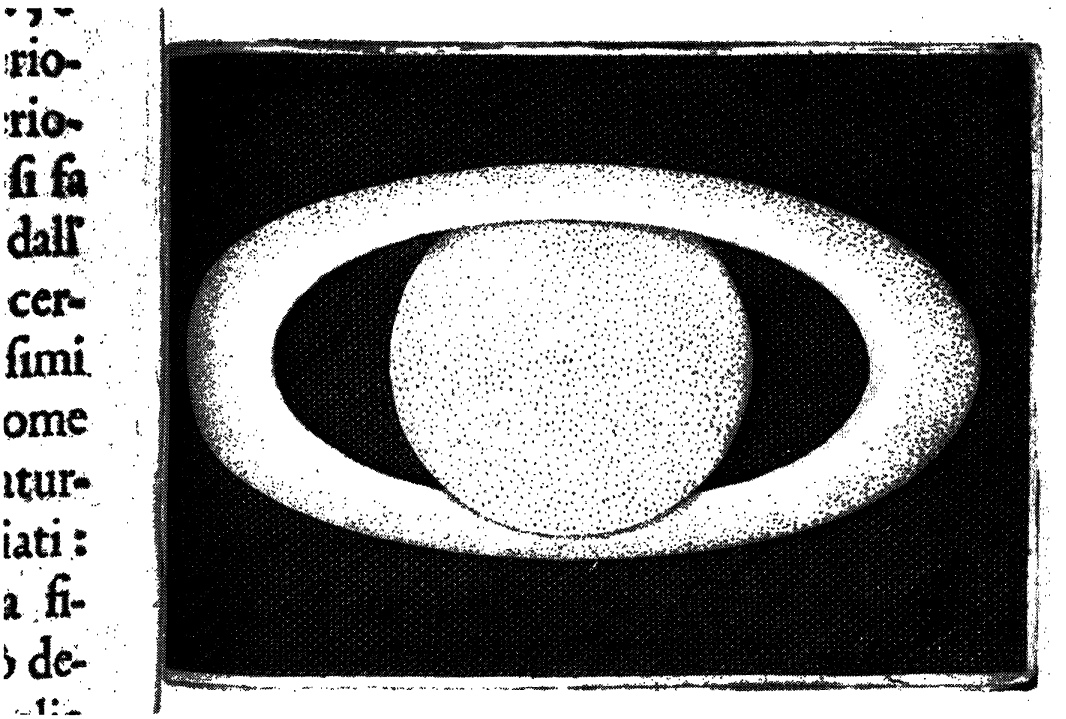

FIG. 8. Saturn as seen by Campani in 1663; from *Ragguaglio di due nuove osservazioni.*

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But Auzout took Campani to task for this observation. He agreed with Campani's observation of the shadow of the body on the ring, shown near the bottom of Figure 8. But he did not agree with the observation of the continuous dark band adjacent to the interior edge of the ring near the top of the figure. In his *Lettre à M. l'Abbé Charles* of 1665 he wrote:

> As to the shadow at the top [see Figure 8], which he claims is cast by the ring on the body of Saturn, he cannot have seen it since it should not be visible on account of its northern latitude. . . . It must be the case, therefore, that there is a bit of prejudice in this observation. But nothing is more natural, because once it is admitted that what is seen about Saturn is a ring which surrounds it, one can hardly prevent oneself, when seeing two dark points, from picturing them as continuous from one to the other, especially when the air or the telescope vibrates. And I admit that since I have seen [Campani's] figure, it has appeared to me sometimes that I saw the continuation, especially, as I said, when the air vibrated. But when observing, as I always try to do, without thinking of that or any other shape, it appears to me as if those two bodies [the ring and the central globe] are one continuum in that place.[103]

Campani had indeed spoken of "lightly shadowed outlines", and Auzout argued that since the geometry of the situation predicted no shadow of the ring on the body, Campani could not have seen this dark band. It never occurred to Auzout (or anyone else, for nearly two centuries) that one could equally well argue that since no shadow was predicted in the place where Campani showed a dark band, this band had to be something else. Campani had observed the so-called crêpe ring.[104]

The telescope maker stuck to his guns. With regard to another observation of Saturn which he published also in 1664, shown here in Figure 9, he wrote to the Abbé Charles:

> (1) The circle, in the outer part, that is, towards the exterior circumference, is less lucid and clear, up to the middle of its plane, and from the middle towards the disk of Saturn it is more lucid and clear than the same disk.
>
> (2) Here and there, towards the superior part, the extremity of the disk appears a bit darkened, that is, less clear than the remainder of the disk . . . which I have not said nor ever believed to be caused by the shadow of the circle, leaving the judgment of this to astronomical men. . . .
>
> (3) The circle is a bit shadowed by a band neighbouring the apparent inferior part of the globe.[105]

Not only had Campani seen the crêpe ring; he had also noticed the difference in brightness between the outer ring and the second ring, although he had not seen their separation.

Observations such as these, clearly showing that the ring passes in front of and behind the central globe, proved that the hypotheses of Hevelius, Odierna, Fabri, and even Wren were no longer tenable, Auzout wrote in his *Lettre à M. l'Abbé Charles:*

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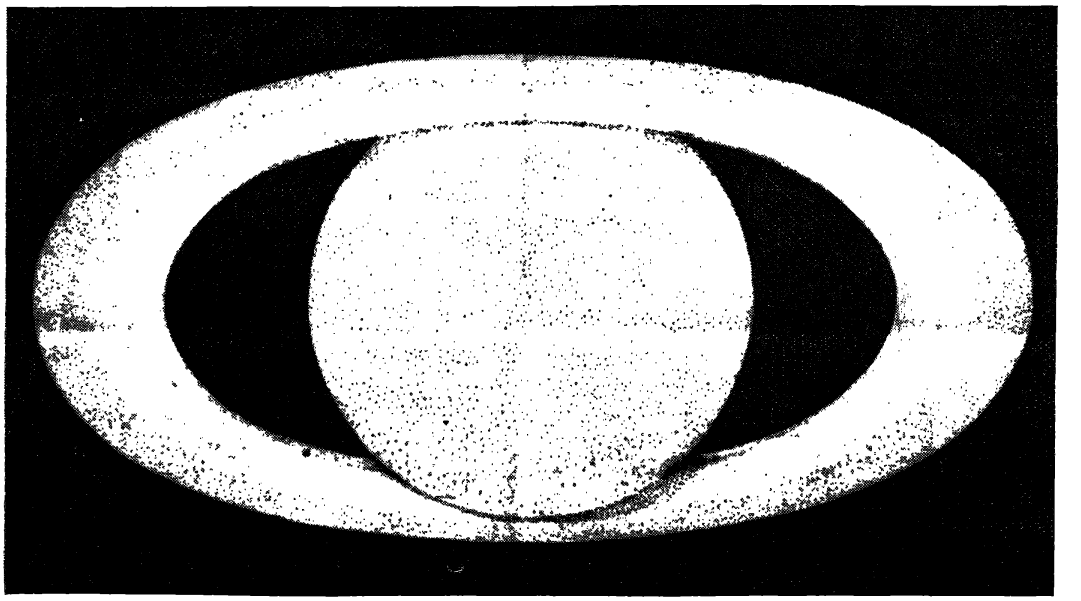

FIG. 9. Saturn as seen by Campani in 1664; from *Oeuvres complètes*, v, facing 118.

> . . . it seems to me that the existence of the ring can no longer be doubted after so many observations of the shadow which the body of Saturn casts on it, conforming to what should happen according to that hypothesis. . . .[106]

He was quite right. Observations of these shadow effects had been made in Italy, France, Holland, and England, and had found wide circulation.[107] They conquered the last remaining opposition to the ring-hypothesis over the next few years.

The watershed was Fabri's acceptance of Huygens's hypothesis, an event of which Huygens was notified early in 1665, and which gave him great satisfaction.[108] But in that same year Riccioli's *Astronomia reformata* appeared, in which the ring-hypothesis was criticised. Riccioli felt that Huygens had not sufficiently explained how the various spurious appearances could be the result of a ring seen through an inferior telescope. He also pointed out the problem of the inclination of the ring. But most importantly, Riccioli preferred an elliptical ring, touching the central body at two points, and which either stayed parallel to itself or revolved or librated about the major axis of the ellipse: *armilla cingitur tenui, plana, Elliptica, duobus locis cohaerente; sive parallela Aequatori; sive in se circumvolubili, aut libratili versus Mundi Polos.* He thought moreover that where the ring touched the central body its parts were narrower than they were at the extremities. This would explain why the connections between the extremities and the central globe are sometimes invisible, causing the planet to appear flanked by two detached bodies.[109] Again, the hypothesis first suggested by Wren had occurred independently to another scientist. Riccioli was probably somewhat out of touch with the most recent developments, for the latest observation mentioned in this section dated from 13 May 1661.

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Clearly, by 1665 men like Riccioli were in the minority. It would be impossible and fruitless to trace the dates of the last conversions. Suffice it to say that by 1670 the ring-hypothesis was no longer an hypothesis: it was accepted as a fact by the scientific community that Saturn was surrounded by a ring. But this ring was generally thought to be very thin, and its inclination was known to be much greater than had first been thought by Huygens. What remained to be done now, was to see how accurate Huygens's predictions as to the next period of invisibility had been, and also to see the anses grow thinner and thinner and finally disappear. Huygens had predicted that the anses would disappear in July or August 1671 and remain invisible until July or August 1672. In fact, the anses disappeared towards the end of May 1671, which was considered fairly close to the predicted time. But in August they became visible again![110] Huygens quickly determined the cause of this unexpected behaviour: when the ring disappeared, the planet was near station, and when it became retrograde the ring became visible again. He predicted that the ring would disappear again towards the end of that year, and this prediction was published by Cassini in November.[111] In early December the anses disappeared once more, and when Saturn became visible again after conjunction, in June 1672, they were clearly visible.[112]

Huygens's predictions, then, were fairly accurate, and much more accurate than those of Hevelius, which were off by a whole year.[113] The predictions for the edgewise appearances of 1685 and 1701 were now adjusted, and these did occur very near the dates predicted by Huygens.[114] Thus, by 1672 the "Saturnian System" of Christiaan Huygens had been sufficiently adjusted to be an entirely satisfactory astronomical explanation of the appearances of Saturn, and it was never again seriously challenged.

Discoveries of new phenomena around Saturn had not ceased in the meantime. Successive edgewise appearances allowed astronomers to scrutinise the sky adjacent to Saturn more closely, not hindered by the glare of the ring. At such times also, satellites which lie in the plane of the ring will appear to move roughly on the straight line of the anses, much like the satellites of Jupiter.[115] In 1671, 1672, and 1684, Cassini discovered a total of four new satellites of Saturn, all through Campani telescopes. Those discovered in 1684 were never seen by Huygens, who had returned to The Hague for good.[116] In 1675 Cassini made another, quite unexpected discovery: he saw that the dimmer outside part of the ring and the brighter inside part are separated from each other.

By the end of the seventeenth century, then, the problem of Saturn's appearances had been solved, and its solution was one of simplicity and elegance. A thin ring (or rather several coplanar thin rings) could account for all the puzzling appearances of Saturn which had mystified observers during the first half of the century. Moreover, the times of future occurrences of the edgewise appearances of these rings could be predicted with a high degree of accuracy. Whereas interest in a scientific problem usually wanes once a generally accepted solution has found its way into the textbooks, in the case of Saturn the uniqueness of the spectacle and the elegance of the solution to a seemingly intractable problem has never ceased to fascinate scientists and laymen.

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1. P. Gassendi, *Opera omnia* (Lyons, 1658), iv, 480.
2. A. Van Helden, "Saturn and his Anses", *Journal for the history of astronomy*, v (1974), 105–121.
3. A. M. Clerke, *A popular history of astronomy during the nineteenth century*, first ed. (Edinburgh, 1885), 111.
4. Van Helden, *op. cit.*, 110, fig. 1; 117, fig. 8.
5. The realisation that Saturn is surrounded by not one but several rings dates from J.-D. Cassini's discovery of the division named after him. In order to avoid confusion and anachronism, therefore, I shall treat the two bright rings as one ring in this paper.
6. I have put the word "seeing" in inverted commas here because seeing a globe also involved mental interpretation. Properly speaking, in the absence of surface markings and shadow effects, observers before about 1660 could only see a disk.
7. R. Grant, *History of physical astronomy* (London, 1852), 257.
8. On 8 March 1656 Huygens wrote to Hevelius: "Only last year did I learn the art of making telescopes, nor do I have earlier observations". *Oeuvres complètes de Christiaan Huygens* (The Hague, 1888–1950), hereafter *O.C.*, i, 388.
9. *O.C.*, xv, 172, 238.
10. *O.C.*, i, 332, 335. The anagram, *Admovere oculis distantia sidera nostris vvvvvvv cccrrhnbqx*, is a popular line from Ovid's *Fasti*. Huygens also inscribed this line (without the supplementary letters) on the objective lens of the 12ft telescope with which he discovered the satellite. *O.C.*, xv, 11.
11. *O.C.*, i, 392. The solution was: *Saturno luna sua circunducitur diebus sexdecim horis quatuor.*
12. *O.C.*, xv, 15, 238, 246.
13. *O.C.*, i, 380.
14. Hevelius to Boulliau, 9 December 1659, Bibliothèque Nationale MSS Fonds Français 13043, f. 89v–90r. Wallis to Huygens, 1 January 1659, *O.C.*, ii, 306.
15. *O.C.*, xv, 176.
16. Between the construction of his first pendulum clock in December 1656 and the publication of *Horologium* in September 1658, Huygens made virtually no progress in the preparation of his "System of Saturn" for publication (see *e.g.*, *O.C.*, ii, 220–221), although he did continue his observations of the planet and its satellite.
17. Hevelius to Boulliau, 22 June 1656, Observatoire de Paris MSS "Epistolae Hevelium", iv, no. 458.
18. The tract was not written as a response to Huygens's challenge (*O.C.*, i, 411–12, 434–5).
19. J. Hevelius, *Selenographia* (Gdansk, 1647), facing p. 42. See also Van Helden, "Saturn and his Anses", 116, fig. 7.
20. Johannes Phocylides Holwarda, *Philosophia naturalis seu physica vetus-nova* (Franeker, 1651), 259–60.
21. *Johannis Hevelii Dissertatio de nativa Saturni facie, ejusq; variis phasibus certa periodo redeuntibus* (Gdansk, 1656), 1–4.
22. *Ibid.*, 12–13; 29–30; plate G, facing p. 12; plate H, facing p. 30.
23. *Ibid.*, 6.
24. *Ibid.*, 16, 17.
25. *Ibid.*, 21.
26. Huygens to Hevelius, 25 July 1656, *O.C.*, i, 413. Antonius Vatier to Hevelius, 3 April 1656, British Museum MSS Sloane 652, 189–90. For Wren's comments on this hypothesis see *O.C.*, iii, 422–3, and A. Van Helden, "Christopher Wren's *De Corpore Saturni*", *Notes and records of the Royal Society*, xxiii (1968), 213–29, p. 224.
27. *O.C.*, i, 488–9.
28. See *e.g.*, Van Helden, "Saturn and his Anses", 117–18.
29. *O.C.*, i, 474–6; ii, 165–6; xv, 288–90.
30. *O.C.*, i, 474–6.
31. *O.C.*, i, 486.
32. *O.C.*, ii, 175.
33. G. B. Odierna, *Protei caelestis vertigines seu Saturni systema* (Palermo, 1657), 22.
34. The tract was dated 20 December 1656, but bears the publication date 1657.
35. Odierna, *op. cit.*, 5.

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36. *Ibid.*, 3–4.
37. *O.C.*, iii, 140; xv, 290–2.
38. *O.C.*, iii, 420; Van Helden, "Christopher Wren's *De Corpore Saturni*", 221.
39. *O.C.*, ii, 305.
40. Van Helden, "Christopher Wren's *De Corpore Saturni*", 223–4; *O.C.*, i, 481. See also, A. Armitage, "William Balle, FRS (1627–1690)", *Notes and records of the Royal Society*, xv (1960), 167–72.
41. *O.C.*, i, 482.
42. *Ibid.*
43. *O.C.*, iii, 417.
44. Van Helden, "Christopher Wren's *De Corpore Saturni*", 221–2.
45. *Ibid.*, 221. Wren also wrote: "Then, with Saturn reaching about mean longitude, [the anses] are seen to suddenly disappear. At that time, the globe appears indeed solitary because both the sun and the eye are in the plane of the corona, which, because it has no sensible thickness—although it is perhaps a few miles thick—must escape the keenest of sight because of the great distance, thus leaving the globe utterly bare" (*ibid.*, 222).
46. *Ibid.*, 224.
47. *Ibid.*, 223.
48. *O.C.*, iii, 417.
49. *O.C.*, xv, 176.
50. *O.C.*, xv, 39, 238–9; i, 322.
51. The anses became visible again in October 1656 (*O.C.*, xv, 246), seven months after Huygens had published *De Saturni luna*.
52. *O.C.*, xv, 238–40, 296.
53. *E.g.*, *O.C.*, xv, 239, 240.
54. *O.C.*, xv, 294–6.
55. *O.C.*, ii, 109–10, 157–61, 166, 169, 173–6. See also H. Brown, *Scientific organizations in seventeenth century France* (Baltimore, 1934), 84.
56. *O.C.*, ii, 330–1.
57. *O.C.*, xv, 228–38.
58. He calculated the sidereal period to be $15^{d}22^{h}39^{m}$, and the synodic period $15^{d}23^{h}13^{m}$. These values were based on about 68 circuits of the satellite. In 1683 Halley corrected the sidereal period to $15^{d}22^{h}41^{m}6^{s}$, which differs from the modern value by only a few seconds (*Philosophical transactions*, xiii, no. 145 [10 March 1683], 82–88).
59. *O.C.*, xv, 270.
60. *O.C.*, xv, 298.
61. *O.C.*, xv, 309.
62. See *e.g.* the illustration on *O.C.*, xv, 299.
63. *O.C.*, xv, 318.
64. *O.C.*, xv, 318–20. The editors of the *Oeuvres complètes* point out that on at least four occasions between 1655 and 1659, cited in *Systema Saturnium*, Huygens shows a dark band on the planet adjacent to the exterior edge of the ring, while on the dates in question the shadow of the ring on the body should have appeared adjacent to the interior edge of the ring. The only explanation, according to the editors, is that on those occasions Huygens saw the contrast between the bright ring and one of the darker equatorial belts of Saturn (*O.C.*, xv, 202–3).
65. *O.C.*, iii, 18.
66. *O.C.*, ii, 510.
67. *O.C.*, xv, 214.
68. *O.C.*, ii, 510–11.
69. Bibliothèque Nationale MSS Fonds Français 13043, f. 89v–90r.
70. *Ibid.*, f. 90v.
71. *Ibid.*
72. *Ibid.*, f. 92r.
73. *Ibid.*, f. 90v.
74. *O.C.*, iii, 92–93.
75. *O.C.*, iii, 95, 134.

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76. *Ibid.*
77. *O.C.*, xv, 210.
78. Prince Leopold very often ordered his academicians to perform certain experiments. See W. E. Knowles Middleton, *The experimenters, a study of the Accademia del Cimento* (Baltimore, 1971), 56–61.
79. *Eustachii de Divinis Septempedani brevis annotatio in systema Saturnium Christiani Eugenii . . .* (Rome, 1660), reprinted the same year with Huygens's response, *Brevis annotatio . . . una cum Christiani Hugenii responso* (The Hague, 1660), in *O.C.*, xv, 401–37.
80. *O.C.*, xv, 426–36. See also, A. Van Helden, "The Accademia del Cimento and Saturn's Ring", to appear in *Physis*.
81. *Christiani Hugenii Zulichemii brevis assertio systematis Saturnii sui* (The Hague, 1660), *O.C.*, xv, 462–4.
82. *Eustachius de Divinis Septempedanus pro sua annotatione in systema Saturnium Christiani Hugenii adversus ejusdem assertionem* (Rome, 1661), 56–58.
83. *Ibid.*, 106.
84. *O.C.*, v, 176, 193. H. Fabri, *Dialogi physici, in quibus de motu terrae disputatur* (Lyons, 1665), 212. See also Fabri, *Synopsis optica* (Lyons, 1669), 49–59.
85. *O.C.*, iii, 151, 157, and the figure between 154 and 155.
86. *O.C.*, iii, 154–5.
87. See *e.g.*, *O.C.*, iii, 149–50.
88. *O.C.*, iii, 194–7.
89. *O.C.*, xv, 109–10, 153.
90. *O.C.*, xxi, 786.
91. *O.C.*, iii, 351–2.
92. *O.C.*, iii, 283, 352.
93. *O.C.*, iii, 350–3.
94. *O.C.*, iii, 350–1, 338.
95. *O.C.*, iii, 332, 368. T. Birch, *The history of the Royal Society of London* (London, 1756–57), i, 43.
96. *O.C.*, iv, 34.
97. *O.C.*, v, 257, 368.
98. *O.C.*, xv, 483–4. See also "Observation de Saturne faite a la Bibliotheque du Roy", *Journal des sçavans*, 11 February 1669, 11–12.
99. *O.C.*, xv, 479. The ratio 9:4 is very close to the modern value.
100. He finally observed this shadow effect in the summer of 1664 (*O.C.*, v, 109–10.) For a discussion of the relative merits of the telescopes of Huygens and Divini, see A. Van Helden, "Eustachio Divini versus Christiaan Huygens: a Reappraisal", *Physis*, xii (1970), 36–50.
101. G. Campani, *Ragguaglio di due nuove osservazioni* (Rome, 1664), facing p. 8.
102. *Ibid.*, 18.
103. A. Auzout, *Lettre à M. l'Abbé Charles* (Paris, 1665), 7. This letter was written in October 1664.
104. When the so-called crêpe ring was discovered in 1850, it was quickly pointed out that it had been sighted on several occasions in the seventeenth century, Clerke, *op. cit.*, 113.
105. Campani to the Abbé Charles, quoted in *O.C.*, v, 117, n.l.
106. Auzout, *op. cit.*, 9.
107. *E.g.*, Hooke's observation of June 1666 was published in the *Philosophical transactions*, i, no. 14 (2 July 1666), 246, and plate.
109. G. B. Riccioli, *Astronomiae reformatae tomi duo* (Bologna, 1665), 367–8.
110. *O.C.*, vii, 101.
111. J. D. Cassini, *Suite des observations des taches du Soleil faites à l'Académie Royale. Avec quelques autres observations concernant Saturne* (Paris, 1671). Oldenburg printed the prediction in the *Philosophical transactions* of 18 December 1671. See also *O.C.*, vii, 115–16.
112. "Extraict d'une Lettre de M. HUGENS de l'Academie Royale des Sciences à l'Auteur du Journal des Sçavans, touchant la figure de la Planete de Saturne", *Journal des sçavans*, viii (12 December 1672); *O.C.*, vii, 235.
113. Hevelius, *De nativa Saturni facie*, 17.
114. *O.C.*, vii, 237.

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115. The first eight satellites of Saturn were discovered when the ring was in or near its edgewise poition. Phoebe, discovered by Pickering in 1898, was the first satellite of Saturn to be discovered when the ring was not near its edgewise position, but this discovery was made with the help of photographic techniques.

116. *O.C.*, xv, 46.

117. "Observations Nouvelles de M. Cassini, touchant le Globe & l'Anneau de Saturne", *Journal des sçavans*, 1 March 1677, 32–33. The claim that William Balle had already noticed this separation in 1665 (*e.g.*, Grant, *op. cit.*, 526), is erroneous. Balle's observation can be found in *O.C.*, v, 543. This figure was omitted from the article in the *Philosophical transactions*, i, no. 9 (12 February 1666), 152.

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